Tyndall National Institute
Institiúid Náisiúnta

Is Ireland ready for Quantum Technologies?

Executive Summary

Underlying our Tyndall 2025 strategy is a commitment to invest with ambition in areas of growth where Quantum Technologies feature prominently. These comprise a suite of novel engineering solutions to challenging problems using the fundamentals of quantum science. They offer an uncharted fertile arena for innovation that has sparked an international arms race to attain quantum advantage. Tyndall has been pioneering Irish efforts in the field, specifically on the actual realisation of Quantum Technologies and within Tyndall 2025 we will foster the development of new programmes around novel quantum materials and nanostructures and their translation into disruptive devices for Quantum Technologies. This activity is complemented by UCC's strategy and the recent appointment of Prof. Séamus Davis.

On this opportunity, we call the Irish Government and the scientific community to embark on a programme for Quantum Technologies. Despite a slow start, Ireland is still in unique position to become internationally competitive and attractive thanks to long-term investments in materials and engineering science for digital technologies and the strong footprint of technology giants with significant investments in the field. For Ireland to succeed, it is timely to take action by:

- Establishing Quantum Research as a Priority
- Developing Quantum Technology hardware utilizing Ireland's Strengths for example in Photonics and Nano-electronics
- Committing Infrastructure for Quantum Technologies, e.g., a National Quantum Institute
- Investing in Educating Quantum Scientists and Engineers

Tyndall National Institute, Lee Maltings, Dyke Parade, Cork, Ireland. T12 R5CP
t +353 21 490 4177 e info@tyndall.ie w tyndall.ie
@TyndallInstitut Tyndall National Institute

State-of-play on Quantum Technologies

Quantum mechanics is more than a hundred years old. Its fundamental equations were established in early last century and have developed to yield quantitative predictions of our physical world with incredible precision. Modern era technology has been built on our understanding of quantum effects: semiconductors, transistors, lasers, organic chemistry, magnetic resonance etc. However, quantum mechanics is full of oddities and surprises. One can simply understand and exploit most of quantum mechanics by thinking of particles as waves. But the underlying concepts are so unfamiliar to humankind that we have barely scratched the surface. A fundamental turning point occurred in 1964 when John Bell, a northern Irish physicist, discovered what is now known as Bell's inequalities. Bell's set of equations definitively prove not only the full wave nature of fundamental particles but also that there is mutual dependence (so called entanglement) which appears to violate causality. In simple terms, the rules of quantum physics state that an unobserved particle exists in all possible states simultaneously but, when observed or measured, exhibits only one state. When two particles are prepared in such a superposition (entangled) state they remain connected so observing the state of one immediately affects the other, even when separated by great distances. This is what Albert Einstein called "spooky action at a distance." As an increasing number of experiments have been devised to test such oddities, the new discoveries are allowing us to embark on a second quantum technological revolution and exploit the laws of quantum mechanics to perform computation, communicate and sense. Quantum advantage would allow outperformance of classical computers in problems of increased complexity, guarantee secure communication and achieve the highest possible sensitivities in sensor technologies.[1]

The growing realisation of the opportunities arising has already kick-started an international race on turning the excellent achievements of quantum science in recent years into a national competitive advantage in Quantum Technologies.[2] Strong innovator countries such as USA, UK, Germany, Netherlands, Australia, Japan, Singapore and Canada have been heavily investing in strong quantum technology research programs amounting to several billion; China has also commenced in this direction with huge strides, including a strong space program for secure quantum-based communications. [3,4] China for now dominates the field of quantum communication whereas US firms lead in the development of quantum computation. To ensure strategic and economic sovereignty, the European Union has responded by committing into an over €1bn investment over the next 10 years to support a variety of quantum technology platforms.[5] The wealth of business opportunities existing in quantum computing, cryptography, communication, simulation and sensing has also triggered investments from major private companies. Quantum Technologies are now major research topics

1 'Quantum Technologies Roadmap', EC Quantum Flagship community (2016)
2 'Quantum Technologies: Implications for European Policy. Issues for debate', European Commission (May 2016)
3 The Race to Develop the World's Best Quantum Tech, IEEE Spectrum (January 2019)
4 EU runs to catch up as governments pledge more cash for quantum computing, SCIENCE¦BUSINESS (October 2018)
5 Quantum Technologies Flagship (October 2018)

for IBM, Google, Microsoft, Intel and other technology giants. Quantum computers promise to considerably speed up solutions of a number of computational tasks, realising the only known model that could offer exponentially faster computing over today's conventional processors.
Besides we are at a pivotal time where traditional scaling as encompassed by Moore's law is coming to an end.[6,7,8] While the amount of data to be handled and analysed is constantly exponentially growing next generation information and communication technologies (ICT) will demand scientific and technological paradigm shifts. Radical advances will require new concepts to be invented, new materials and their fundamental properties to be understood, and new fundamental principles to be explored.[9]

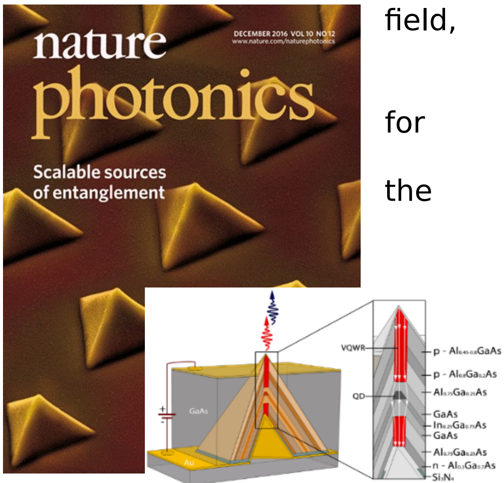
Irish context

Despite the growing significance of Quantum Technologies and their importance for international competitiveness the national position of Ireland lags considerably behind leader and follower countries alike. While the Irish Government, and the Department of Business, Enterprise and Innovation (DBEI) recognise the impact of digitalisation and have re-emphasised their commitment to embracing ICT innovation and technological change under Pillar 1 of the recently published policy 'Future Jobs Ireland 2019', there is no indication of recognising Quantum Technologies as research priority. In 'Technology Skills 2022', co-signed by the Department of Education and Skills (DES), there is significant emphasis on high-level ICT skills, such as computing and electrical and electronic engineering skillsets. This is recognisably instrumental to deliver in the short-term on the high industry demand for skills in the design, building and maintenance of ICT systems. However, it would be a mistake to assume that ICT innovations in the future and for Project Ireland 2040 can be built without preparing a new generation of scientists and engineers with substantial knowledge in both quantum mechanics and also its technological applications. Besides the commercial potential of the sector itself, there are significant gains to be earned by applying Quantum Technologies in Ireland's foremost industries; examples include: digital (machine learning, artificial intelligence, cybersecurity), pharmaceutical (drug design), finance (pricing, risk optimisation), industrial goods and energy (materials chemistry, compound selection), manufacturing (highly AI-efficient processes). Not investing now in such a disruptive technology and complementary skills, will result in Ireland missing the window of opportunity to utilise the current baseline to attract and stimulate substantial business growth.

6 'Is the semiconductor industry entering a new phase when it comes to scaling?' newelectronics (June 2016)
7 'Beyond Scaling: An Electronics Resurgence Initiative', Power Electronics (June 2017)
8 'Roadmap Says CMOS Ends ~2024', EE|Times (March 2017)
9 'NanoElectronics Roadmap for Europe: From Nanodevices and Innovative Materials to System Integration', J. Ahopelto, G. Ardila, L. Baldi, F. Balestra, D. Belot, G. Fagas, S. De Gendt, D. Demarchi, M. Fernandez-Bolaños, D. Holden, A. M. Ionescu, G. Meneghesso, A. Mocuta, M. Pfeffer, R. M. Popp, E. Sangiorgi, C. M. Sotomayor Torres, Solid State Electronics (2019)

While there is no strong centre of gravity in Quantum Technologies in Ireland, there is an underlying quantum research and enterprise community that given the right conditions can gain momentum and thrive internationally as an attractor for investment and growth. First, there is a growing number of high-profile experimental outputs complementing theoretical studies of academic groups around the country on the fundamentals of quantum mechanics and how these may apply to computation. All seven constituent universities of Ireland have research groups which are either directly involved in research in quantum technologies or their research has potential to converge to quantum technologies in foreseeable future. For example, quantum computation theory is strongly represented at Maynooth University with complementary research emerging at TCD and NUI Galway. Moreover, an ambitious effort has recently been undertaken at UCD to address issues from the electronic engineering perspective. Second, most of the key technology firms who have been investing in Quantum have a strong Irish footprint. Notably, IBM who have been running one of the most comprehensive Quantum Computing programmes are conducting research in Ireland on applications of quantum algorithms for optimization, executed on quantum computing hardware and simulators, over the cloud.[10]

Tyndall position



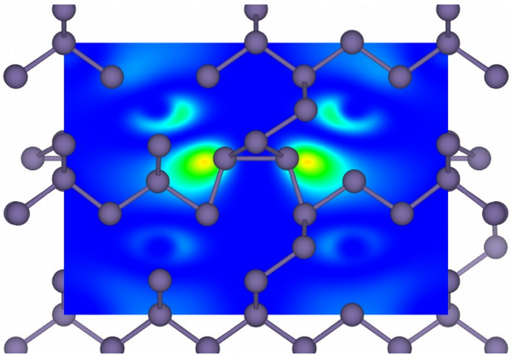
Tyndall has been pioneering Irish efforts in the field, specifically on the actual realisation of Quantum Technologies. Quantum cryptography for secure communications and sources of quantum light for quantum information (quantum internet and quantum computation) have been at the core of the Institute's effort. Besides one of our research centres led by one of the founders of the field of experimental Quantum Key Distribution (QKD), our research teams have been investing in quantum materials and quantum-effect devices for over 15 years and this activity is finally paying off.[11] An optical quantum platform based on site-controlled III-V quantum dots has been uniquely developed in the group of Epitaxy and Physics of Nanostructures. This platform has demonstrated the only site-controlled quantum dot system capable of high fidelity entangled light emission, making it a most promising scalable platform for solid-state quantum computation and communication. Amongst the particles investigated to date for quantum information technologies, photons are the least prone to decoherence due to weak interaction with their environment. The Tyndall nanostructures represent a

---

10 See e.g. Andrea Simonetto, Jakub Marecek, Martin Mevissen, "Qiskit Aqua: Vehicle Routing" and "Qiskit Finance: Portfolio diversification"

11 See e.g. Gediminas Juska, Valeria Dimastrodonato, Lorenzo O. Mereni, Agnieszka Gocalinska and Emanuele Pelucchi "*Towards quantum dot based arrays of entangled photon emitters*", Nature Photonics 7, 527 (2013).;T. H. Chung, G. Juska, S. T. Moroni, A. Pescaglini, A. Gocalinska and E. Pelucchi, "*Selective carrier injection into patterned arrays of pyramidal quantum dots for entangled photon light-emitting diodes*", Nature Photonics 10, 782–787 (2016)

deterministic source of on-demand non-classical light, a fundamental pre-requisite for any optical quantum information protocol. Quite remarkably, sources based on quantum dots do not have any fundamental physical limitation in their potential to deliver quantum signals deterministically and on-demand. In addition, Tyndall researchers and the CAPPA@Tyndall group of CIT are exploiting their expertise in quantum modelling and integration of nanophotonics to deliver single photon sources for quantum cryptography as core partners in CUSPIDOR,[12] the sole project with Irish participation funded under the Quantum European Research Area Network QUANTERA. Tyndall is also very active in European forums, coordinating the 'Quantum in Space' network and contributing to the Strategic Research Agenda of the Quantum Technology Flagship.



As Tyndall implements its Tyndall 2025 strategy of ambition and growth, we are committed to foster the development of new programmes around novel quantum materials and nanostructures and their translation into disruptive devices for Quantum Technologies. Tyndall has recently launched the CMOS++ programme to enable Deep Tech innovation for next generation of computing technologies by bringing together frontier research in modelling, metrology and characterisation, materials processing and device fabrication. One of the key deliverables of the programme is to demonstrate quantum advantage using solid-state platforms which are CMOS compatible. As Ireland's flagship ICT hardware research infrastructure Tyndall is in a unique position to realise such quantum platforms and engage with industry to accelerate innovation path-finding as first step towards commercialisation. Tyndall operates a number of cleanrooms with fabrication lines in nanoelectronics, compound semiconductors, and MEMS. These are fully supported by on-site expertise with extensive suite of equipment on test, characterization and packaging (photonic & electronic). In 2006-2010, the Irish Government, through its Programme for Research in Third Level Institutes, invested in the development of 'FlexiFab' at Tyndall to complement the existing silicon and semiconductor fabrication facilities. Overall, more than €100m has been invested in the Tyndall infrastructure since 2004, and further investment is foreseen under the Irish Government's National Development Plan (NDP) 2018-2027, which includes an objective to upgrade and expand Tyndall in response to evolving ICT-related technology opportunities and to strengthen its successful industry engagement model. As part of the NDP Tyndall development, we are planning to support our CMOS++ programme with specialised cryo-magneto-probe infrastructure that will provide a unique in the world electronic and optical characterisation suite for quantum materials and devices. At the end of this implementation phase we will be in the distinct position to build our own on-chip quantum computing platform and address a range of important issues in solid-state qubit technologies. Tyndall's strength will be enhanced by partnering with distinguished quantum physicist Prof. Séamus Davis who will lead a pioneering

12 Compatible Single Photon Sources based on SiGe Quantum Dots (www.cuspidor-quantera.eu)

research programme on direct, atomic-scale visualisation of electronic states in quantum materials.

Call to action

Demonstrating technologies where quantum mechanics yields an advantage is the holy grail of a new generation of physicists and engineers. This notion also receives close review by established top-tech players and newly formed companies in Ireland. Tyndall recognises there are demanding scientific and technological challenges to be overcome and short term expectations are idealistic. Nevertheless the progress in the last 20 years has been truly exceptional, and quantum technologies are already moved outside the mere academic environment, into the real world. For example, quantum cryptographic systems have already gone commercial, magnetic sensors based on diamond NV centres are in an advanced development state for biomedical applications, and atomic traps are already tested to map the earth gravitational field non-uniformities, or more profitably discover new oil fields. Delivering on Tyndall 2025 and growing our research base, one of our key objectives is to strengthen the link with the industry to nurture the growth of Quantum Technologies by translating science to innovation and by developing and attracting talent with quantum expertise in Ireland. This effort requires a coordinated and synergetic national engagement with specific actions supported by the government and its agencies.

Establish Quantum Research as a Priority – Intensify support to fundamental research and disruptive technologies delivering quantum advantage, in alignment with Ireland's ambitious goals in increasing investment in research, development and innovation (RD&I) and promoting strong links between enterprise and the research community. Such an endorsement will create momentum within the fragmented Irish quantum community.

Develop On Chip Quantum Computer – Designs based on solid-state nanostructures and advanced materials are most promising as they are scalable and would be easier to integrate with conventional semiconductor technologies. Ireland's strengths in nanoelecronics and quantum materials can be utilised to drive CMOS-based quantum computing architectures. Ireland is in a unique position to leverage existing expertise and mobilise the currently forming critical mass to become world pioneer by building the first quantum computer on an optical quantum platform, thereby fostering enterprise growth.

Commit Infrastructure for Quantum Technologies – Invest in institutes such as Tyndall to acquire the necessary equipment and build dedicated facilities to support the establishment of a National Quantum Institute (e.g., using the organisational structure of an SFI research centre or equivalent). Embedding in an already established institute will allow to utilise existing infrastructure and ensure the development of a decision centre with national remit and authority to represent the Irish quantum research and industry community in Europe and globally.

Invest in Educating Quantum Scientists and Engineers – Prioritise the establishment of a national postgraduate school on quantum science and

engineering. No postgraduate programme dedicated to Quantum Science and Technology exists to prepare the next generation of scientists and engineers to develop and exploit the counterintuitive results of quantum research either in academia or industrial settings. The famous physicist Richard Feynman once said ‘if you think you understand quantum mechanics then you don't understand quantum mechanics’.

About Tyndall

Tyndall National Institute is a leading European research centre in integrated ICT hardware and systems. Central to Tyndall's mission is delivering economic impact through research excellence. We work with industry and academia to transform research into products in our core market areas of communications, agri-tech, energy, environment and health.

As the national institute for micro/nanoelectronics and photonics, and a research flagship of University College Cork, Tyndall employs over 450 researchers, engineers and support staff, with a cohort of 120 full-time graduate students. Together we generate over 300 peer-reviewed publications annually. With a network of 200 industry partners and customers worldwide, Tyndall generates 85% of its €35M income each year from competitively won contracts.

Tyndall is home to a high-tech national research infrastructure unique in Ireland and is a national research asset. Hosting the only full CMOS, Micro-Electronic-Mechanical Systems (MEMS) and III-V Wafer Semiconductor fabrication facilities and services in Ireland, Tyndall is capable of creating opportunities and prototyping new products for its target industries.

In recent years we have received international recognition for designing, miniaturising and prototyping products to drive connectivity. Our researchers have won numerous awards for their ground-breaking research on new materials, devices and systems across micro/nanoelectronics and photonics, including in the areas of ICT for Health, Virtual Reality/Augmented Reality (AR/VR), wearables and the Internet of Things (IoT).

We are also a lead partner in European research programmes in electronics and photonics and their integration into smart systems with applications in communications, agri-tech, energy, environment and health. In H2020, we deliver value to European research in 79 projects so far (12 as coordinator).

Tyndall hosts a number of industry-led research centres, including IPIC (Irish Centre for Integrated Photonics), CONNECT (Irish Research Centre for Future Networks and Communications and Microelectronics Circuit Centre Ireland (MCCI). These centres fully encompass the mission of the Institute, i.e. that of representing a critical link between academia and industry, so to expedite the development of new technologies and their market exploitation. Tyndall members are important actors at European level with key representation at High Level Groups, Scientific Councils and European Technology Platforms. We have been contributing to the development and implementation of the Strategic Agendas of ESTHER, AIOTI, AENEAS, EPoSS, and Photonics21.

About the Authors

Dr. Emanuele Pelucchi is Head of Group at Tyndall National Institute, responsible of the MOVPE national facility activities, SFI PI, co-PI in a number of projects, including the IPIC national centre. He holds a PhD in Physics from Bremen university (2001), and subsequently joined EPFL as research assistant. In May 2006, Dr. Pelucchi was awarded a SFI Principal Investigator Grant and moved to Tyndall National Institute in January 2007 where he set up a new research group in the field of III-V epitaxy for device applications, semiconductor (site-controlled) quantum dots and their applications to quantum optics and information. Dr. Pelucchi has very broad interests, spanning from surface science and epitaxy to quantum optics. He has developed world leading III-V material quality (especially in the field of photonic integration) and growth process understanding, while uniquely developing and demonstrating arrays of site-controlled quantum dots and entangled photon emitters.

Dr. Giorgos Fagas MBA is Head of EU Programmes at Tyndall National Institute. He has been leading Tyndall's EU Programmes since late 2013 to engage with academia, industry, other RTOs and policy stakeholders to develop technology roadmaps, shape EU Research and Innovation policies and establish strategic partnerships for collaborative research in Europe and internationally. Giorgos is member of the Digital Innovation Hubs WG, the ESFRI Physical Sciences and Engineering WG, the QCN of the Quantum Flagship, and the AENEAS Scientific Council as well as a regular delegate to the EPoSS Executive Committee where he chairs the Working Group for Smart Systems in Natural Resources. Giorgos is also elected in the executive committee of MIDAS, the Irish industry association for micro and nano-electronics based 'system solutions', to represent their interests in European affairs. Previously, Giorgos has been leading activities in nanoelectronics and energy-efficient electronics as a senior researcher at Tyndall. His research has been published in over 70 peer-reviewed articles. He is also the editor of one reference book on Molecular Electronics and two books on ICT-Energy Concepts.